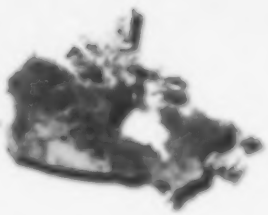

Review and Synthesis of Regeneration Methods in Beetle-Killed Stands Following Mountain Pine Beetle *(Dendroctonus ponderosae)* Attack: A Literature Review

Janet Mitchell, R.P.F.

Mountain Pine Beetle Initiative

Working Paper 2005-16

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Abstract

The current infestation of mountain pine beetle (*Dendroctonus ponderosae*) is having a significant effect on the lodgepole pine forests of Interior British Columbia. By 2004, 7 million hectares had been affected by mountain pine beetle. The impact of this infestation is unprecedented in the last 100 years due to large areas of susceptible pine as a result of aggressive wildfire control activities; warmer, drier summers; and milder winters. In past infestations, a majority of the beetle-killed stands were salvaged and the cutovers were planted or left for natural regeneration. During the current outbreak, it may not be possible to salvage all the beetle-killed trees for reasons of accessibility, location, management objectives, lack of milling capacity, economic factors or other resource values, and some of the beetle-killed stands will be left. A portion of these stands will regenerate naturally over time as part of a natural disturbance pattern with fires and stand succession, but other stands will need assistance to restore them before regeneration is established. This report provides a summary of a literature review examining regeneration issues in lodgepole pine stands killed by mountain pine beetle. It also looks at regeneration following other large-scale natural disturbances, e.g., wildfire and volcanic eruptions.

Résumé

La flambée actuelle de dendroctones du pin ponderosa (*Dendroctonus ponderosae*) a un sérieux impact sur les forêts de pins de l'Intérieur de la Colombie-Britannique. En 2004, 7 millions d'hectares avaient déjà été touchés par le scolyte. L'impact de cette infestation n'a pas eu d'équivalent depuis 100 ans à cause de l'existence de vastes superficies de boisés contenant des pins susceptibles d'être attaqués – résultat des activités de contrôle des incendies, d'étés plus chaud et plus secs et d'hivers plus doux. Lors des flambées précédentes, le bois de la majorité des arbres tués par le scolyte avait été récupéré et les boisés dévastés avaient été replantés ou laissés tels quels pour qu'ils se régénèrent naturellement. Dans le cas présent, il ne sera peut-être pas possible de récupérer tout le bois provenant des arbres tués par le scolyte pour des raisons d'accessibilité, d'emplacement, d'objectifs de gestion, de capacité insuffisante dans les scieries, de facteurs économiques défavorables et d'autres facteurs liées aux ressources. Certains boisés atteints par les scolytes seront donc abandonnés. Une fraction d'entre eux se regénérera naturellement dans le cadre de la dynamique des perturbations naturelles, dont font également partie les incendies, mais il faudra intervenir dans certains boisés afin de les remettre en état pour faciliter l'amorce de la régénération. Le présent rapport présente un résumé des études précédentes portant sur les problèmes de régénération des boisés de pins de Murray tués par le Dendoctone du pin ponderosa. On y aborde également la question de la régénération à la suite d'une perturbation naturelle à grande échelle comme un incendie ou une éruption volcanique.

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1 Introduction

British Columbia has large areas of mature lodgepole pine (*Pinus contorta*) susceptible to the mountain pine beetle as a result of attempted fire exclusion and the lack of logging of this species prior to the 1970s (Pedersen 2004). An outbreak of mountain pine beetle in the 1980s and the current major outbreak have had a large impact on forest management in British Columbia. While most accessible beetle-attacked stands have been salvaged in the past, the scale and intensity of the current outbreak may preclude harvesting of all killed stands before natural degeneration makes it impractical.

Forest managers have in the past regenerated stands using a mix of natural and artificial regeneration methods. In pure lodgepole pine stands this is typically not an issue. Cones will eventually open and over time new regeneration will follow, but in areas where infestation is widespread and seed sources unreliable, forest managers need to intervene. They need to provide a seed source either by seeding or by planting seedlings to ensure adequate regeneration before the free-to-grow regeneration date. Some of these methods are more cost effective than others, but there has never been a review of the methods to evaluate the efficacy of these regeneration techniques or the advantage of one system over another. The Forest Engineering Research Institute of Canada (FERIC) reviewed regeneration methods in the literature that have been tried in mountain pine beetle–killed stands in British Columbia, southwestern Alberta and areas of northwestern USA, with the goal of identifying methods that are both cost effective and operationally applicable to rehabilitate beetle–killed stands. Such information may serve as a reference for future rehabilitation operations in mountain pine beetle-attacked stands and lay the cornerstone for field-orientated research in future years.

1.1 Objectives

1) Catalogue regeneration methods from the literature used in beetle–killed stands;
2) Assess the success rate, cost effectiveness and operational applicability of the regeneration methods;
3) Examine the feasibility of using direct seeding to regenerate large areas salvaged after mountain pine beetle infestations; and
4) Recommend regeneration techniques that show promise for further investigation.

2 Methods

We started with the results from a previous literature search completed for a contract under the Mountain Pine Beetle Initiative (MPBI 2003/2004 Project #3.02). The search was then expanded to include natural regeneration and artificial methods including broadcast seeding, direct seeding and planting in stands harvested after beetle infestation and unsalvaged stands. We looked at regeneration systems that may be feasible for use on a large scale to minimize regeneration cost when rehabilitating beetle–killed stands. These included seeding during site preparation, broadcast seeding (aerial and ground-

based), manual seeding and planting. We also examined the components of the regeneration system where there is the potential for cost savings or an increase in reliability of the method including seed acquisition, seed processing, density control, seedbed quality and seasonal constraints. Two earlier literature compilations pertaining to lodgepole pine regeneration were consulted. Herring (1996) prepared a bibliography on information pertinent to the management of lodgepole pine and included natural and artificial regeneration, while Eremko (1990) compiled a literature review examining natural lodgepole pine regeneration.

Finally, we also investigated regeneration methods following other large scale disturbances such as wildfires, volcanic eruptions, windstorms, and other insects, on a global scale as the treatments may be appropriate in mountain pine beetle–killed stands.

3 Results

The literature contained several references to regeneration of lodgepole pine after harvesting or natural disturbances, although few dealt specifically with regeneration in stands killed by mountain pine beetle.

3.1 Impact of the mountain pine beetle on stand condition

By 2004, seven million hectares had been affected by mountain pine beetles in British Columbia. Two million hectares showed trace amounts and five million hectares showed light to severe levels of attack.[1] In 2003, the mature pine in the red-attack category for the province had doubled to 4.2 million hectares since 2002, although not all trees in this area will have been killed (British Columbia Ministry of Forests 2003). Estimates for mountain pine beetle–killed timber that will remain unsalvaged range from 18 million m^3 in the Lakes TSA to 34 million m^3 for the Quesnel TSA and 200 million m^3 for the province overall (Pedersen 2004; Eng 2004; British Columbia Ministry of Forests 2004; Hawkes et al. 2004; British Columbia Ministry of Forests 2003).

After mountain pine beetle infestation, the condition of the residual stand will depend on the percent of stand killed, the percent of pine in stand, and the abundance and condition of other species. The future of the stand will depend on the size of the area impacted as well as the condition of the residual trees. During an outbreak, mountain pine beetles attack large-diameter (>20 cm) trees so residual stands will have an average diameter less than 20 cm (Shrimpton 1984).

3.2 Regeneration requirements

Successful regeneration of lodgepole pine requires a reliable seed source, viable seed, suitable seedbed, suitable microclimate and predator control (Hedin 1985; Weetman and

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[1] Beetle Information Bulletin. Available online from: http://www.for.gov.bc.ca/hfp/mountain_pine_beetle/SUM_mpb_aerial_survey.pdf [Web publisher: BC Ministry of Forests. March 2005. Viewed March 24, 2005].

Vyse 1990). Mountain pine beetle–killed stands have a variety of residual characteristics depending on the original stand and the severity of the beetle infestation. The conditions required for regeneration may not exist in all stands or be available at the appropriate time. The following sections will look at how mountain pine beetle infestations can affect the quality and availability of the basic requirements for pine regeneration.

3.2.1 Seeds

Lodgepole pine is a prolific seeder and produces a good seed crop every one to three years after age ten (Lotan et al. 1985; Andersson et al. 1999). The cones can remain on the trees for many years (40 years or longer), so the canopy may contain millions of seeds per hectare (Turner et al. 1999; Wagner and Lundqvist 2005; Hellum 1983).

Whether a cone can be serotinous or not cannot be assumed. Pine can have both types of cones on the same tree and mature lodgepole pine switch from producing non-serotinous cones to producing serotinous cones between 7 and 55 years (Armitt 1966; Alexander and Edminster 1981; Bancroft 1996). Anderson et al. (2004) found a high degree of serotiny after age 20. Serotiny varies with provenance (Andersson et al. 1999), geographic location [serotinous cones are not common on coastal lodgepole pine (Armit 1966)], and site quality [where trees on the highest quality sites had mostly serotinous cones (Clark 1974)]. Serotiny also appears to depend on the most recent disturbance. For example, in areas where wildfire frequency is higher, the level of serotiny is higher and vice versa (Bancroft 1996; Anderson et al. 2004; Wheeler and Critchfield 1985; Hawkes et al. 2004). By having both serotinous and non-serotinous cones, lodgepole pine regeneration can occur in either the presence or absence of fire, although it is generally considered a fire-dependent species (Lotan et al. 1985).

Seed from non-serotinous cones is shed as the cones mature but does not contribute to sufficient stocking after fires or logging (Hellum 1983; Smithers 1961). Dispersed seed is only viable for one year (Lotan et al. 1985), but the seeds in serotinous cones remain viable for 50 to 75 years (Pfister and Daubenmire 1975; Lotan et al. 1985). Serotinous cones are sealed with a resin that needs a temperature of 45°-50°C to open (Forest Research Council 1983; Lotan and Perry 1983; Andersson et al. 1999; Armit 1966; Turner et al. 1999). This temperature is met during fire or by radiation from the ground. After harvesting, the cones need to be situated within 15 cm of the forest floor to reach this temperature (Forest Research Council 1983).

Seed that comes from cones in logging slash in large openings will only have one opportunity to regenerate and needs to land on a receptive seedbed for successful regeneration. Lodgepole pine seed dispersal is limited to 60 m (Alexander and Edminster 1981; Lotan and Perry 1983; Lotan et al. 1985). In large openings, seed fall from adjacent trees will not reach all of the opening if they are greater than 60 m away (Eremko 1990).

Seeds collected from stands killed by mountain pine beetle up to 10 years earlier have shown decreased potential germination capacity over seeds from live trees, but still ranged from 70% to 87% (Kolotelo 2004b). Seed collected from live trees are generally at the 95% level. Although the results of the germination tests were low, viable seed did

exist in the cones from dead trees confirming that serotinous cones provide good insulation and protection for the seed even after the tree dies (Kolotelo 2004b).

3.2.2 Seedbed

A suitable seedbed is essential for successful germination of seed. Germination and survival of lodgepole pine seed is highest where suitable conditions exist: full sunlight, mineral soil or disturbed organic, no competing vegetation and seed is protected from temperature extremes, drought and predators (Lotan et al. 1985; Armit 1966; Bancroft 1996; Environment Canada 1982). McLarnon (1999) examined germination success of lodgepole pine two years after harvest and found it depends more on the available soil moisture than the substrate. Germinants were abundant on compacted forest floor because they had better contact with the substrate and access to the moisture. He noted that it was a wet June for both years and that this contributed to the good success of the germinants.

Stands killed by mountain pine beetle but unsalvaged may not have enough ground disturbance to create a suitable seedbed for natural regeneration of lodgepole pine. After the stand breaks up and the trees fall down, soil disturbance may increase, but this can be many years and the seed source may no longer be available (Mitchell and Preisler 1998).

3.2.3 Microclimate

Lodgepole pine is shade intolerant (Amman 1976) but benefits from some slash left on the site to provide shade in extreme conditions (Armit 1966; Lotan et al. 1985; Stuart et al. 1989). Residual overstory can protect germinants and young seedlings from excessive evapotranspiration, extreme heat and frost damage. Mountain pine beetle infestations can remove the protective influence of the canopy by killing the larger diameter pine and negatively affect the conditions at the ground level.

Modifying the canopy cover had both positive and negative impacts on lodgepole pine regeneration in a commercial thinning study to reduce the susceptibility of the pine to mountain pine beetle in the Kootenays (Natural Resources Canada 2001). Thinning the mature stands to 4- or 5-m inter-tree distance increased the frost-free period and reduced the drought period, but lowered the light available for photosynthesis compared to adjacent clearcuts (Natural Resources Canada 2001). Damage during the thinning treatment caused 60% mortality of the advanced regeneration; however, enough light penetrated the residual canopy for the undamaged advanced regeneration to release and for the planted lodgepole pine seedlings to establish.

3.3 Regeneration methods

Lodgepole pine can be regenerated by natural regeneration, by release of advanced regeneration, by planting, and by seeding. The following sections will look at the benefits of each method.

3.3.1 Natural

Eremko (1990) examined establishment and stocking control of natural lodgepole pine regeneration and determined that natural regeneration was not consistent throughout its

range. Stocking problems included inadequate, patchy or excessive stocking. After a disturbance by mountain pine beetle or wildfire, overstocking may result (Eremko 1990). Naturally regenerated pine is often in clumpy patterns as seed that collects on suitable seedbeds with suitable microclimates have the highest survival rates (Bella 1983; Gara et al. 1985). In a study of jack pine (*Pinus Banksiana*) and black spruce (*Picea mariana*) in the boreal forest of Quebec, post-fire regeneration is dependent on the proportion of trees killed, the available seedbed, and granivory rate (Greene et al. 2004).

Serotinous cones are a disadvantage when stands die without fire to break the resin bonds (Hellum and Wang 1985). Natural regeneration will not occur until the trees fall down and the cones are within 15 cm of the ground, where they can accumulate enough heat to break the resin bonds (Armit 1966). Cones need the heat to break the bonds and fire provides the necessary conditions for stand regeneration back to lodgepole pine (Samman and Logan 2000). If fire does not occur, understory trees may release and the stand could shift to shade tolerant species such as Douglas-fir (*Pseudotsuga menziesii*) on warmer sites and spruce (*Picea engelmanni*) or subalpine fir (*Abies lasiocarpa*) on cooler sites (Samman and Logan 2000; Amman and Schmitz 1988; Amman et al. 1988; Amman and Cole 1983; Heath and Alfaro 1990).

Stone and Wolfe (1996) looked at the abundance, composition and distribution of understory vegetation and regeneration in lodgepole pine stands with differing intensities (14% to 95%) of attack by mountain pine beetle. Mean plot biomass increased exponentially as mortality rates of the pine increased. Plant richness was highest at moderate levels of beetle-caused mortality while grasses appeared to suppress pine regeneration when there was no influence of fire (Stone and Wolfe 1996).

Small patches and single-tree removal blocks are expected to regenerate naturally as seed disperses from adjacent trees, but experience is showing that there are many small openings created by salvaging mountain pine beetle–killed pine that are not regenerating naturally (Brown and McClarnon 2001). By 2001, these openings amounted to an estimated 2500-3000 ha in total area affected in the Lakes Forest District (Brown and McClarnon 2001). This is a serious problem if we are to rely on natural regeneration and either viable seed or suitable seedbed is lacking.

In a small test of viability from seed collected from beetle-killed pine trees, the potential germination capacity ranged from 66% to 87%. These results were for unprocessed seed but were considerably lower than the 95% standard required from existing seedlots collected. For seed collected ten years after tree mortality, there is still the possibility that beetle-killed lodgepole pine will provide a source of seed for natural regeneration (Kolotelo 2004b). This would assume a receptive seedbed is available.

3.3.2 Advanced regeneration

Stands with established regeneration of non-pine species will develop into Douglas-fir and subalpine fir stands when the pine is killed by mountain pine beetle (Eng 2004; Stone and Wolfe 1996). In a pure or nearly pure pine stand, advanced regeneration is rare unless there are openings in the canopy (Stuart et al. 1989; Environment Canada 1982).

Rakochy (2005) found 50% of the plots in mixed conifer stands with mountain pine beetle mortality had advanced regeneration (all species), but only 50% of the regeneration was healthy. Lewis-Murphy et al. (1999) found that the regeneration of lodgepole pine that established in gaps after mountain pine beetle infested a mixed stand, released when the overstory was removed. Height growth was best when the entire overstory was removed and logging damage was avoided (Lewis-Murphy et al. 1999). Regeneration could be encouraged by thinning mixed species stands and would result in stands that were less susceptible to mountain pine beetle attack (Safranyik et al. 1999).

3.3.3 Planting

In beetle-killed lodgepole pine stands with no advanced regeneration of other species, planting may be required to increase stocking to an acceptable level.

Large numbers of seedlings will be needed to plant the large clearcuts resulting from harvesting of lodgepole pine during the current infestation of mountain pine beetle (Brown and McClarnon 2001; Pedersen 2004; Kolotelo 2004a). The expected increase in sowing requests will require increased planning by the nurseries and Licensees (Brown and McClarnon 2001). Inventories of lodgepole pine seed for most of the beetle affected areas in British Columbia currently exist on the Seed Planning and Registry System (SPAR)[2]–the provincial seed registry (Kolotelo 2004b). However, with the increase in demand for Superior provenances (B+ sources) of lodgepole pine, seed orchards may not meet the demand in the long term (Kolotelo 2004a).

Planting provides better stocking levels and reduces the regeneration delay over natural regeneration and seeding, but the availability of superior provenance seed and scale of the areas needing planting may require alternative regeneration methods to meet the conditions under the current mountain pine beetle infestation.

Planting resulted in more even stocking than seeding after a burn, and seeding was better than the control for jack pine in Saskatchewan (Chrosciewicz 1988).

3.3.4 Seeding

Seeding can be used to reduce the lag time in natural regeneration and can be used when areas to be regenerated are too large to have seeds in the surrounding stands (Hedin 1985). Seeding includes aerial, ground-based and direct[3] methods.

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[2] Seed Planning and Registry System (SPAR) is a web-based information management system that provides on-line access to a provincial registry of forest seed and ordering system. Available online from: http://www.for.gov.bc.ca/hti/spar/what_is_spar.htm [Web publisher: BC Ministry of Forests. Updated May 27, 2004. Viewed March 23, 2005].

[3] The B.C. Ministry of Forests currently does not recognize direct seeding as a standard reforestation method, except on an experimental condition. BC Ministry of Forests Policy Manual: Resource Management Policy 2.10 – Direct Seeding. Available online from: http://www.for.gov.bc.ca/tasb/manuals/policy/resmngmt/RM2-10.htm [Web publisher: BC Ministry of Forests. Updated July 14, 1998. Viewed March 24, 2005].

Seeding has not been used on a large scale in British Columbia or Alberta to date and inadequate seedbed preparation and drought was reported as the main cause of mortality in the early trials (Hedin 1985; Johnson 1973). Other concerns included seed availability, weather, seed predation, low germination rates and uneven stocking (Hedin 1985; Hellum 1974; Waldron 1974). Aerial seeding by helicopter or fixed-wing aircraft has been successfully used in regenerating jack pine in Ontario, but has some disadvantages (Corbett 1992; Hedin 1985). It uses large amounts of seed that often land on unsuitable seedbeds and there is no control over the spacing. Seeding can be considered a viable regeneration option if there is adequate rainfall, adequate soil moisture, minimal vegetation competition and the seedbed is prepared (Robinson 1974; Rudolph 1974).

Direct seeding is a cost-effective alternative to aerial seeding or planting and can be employed during harvesting, with site preparation or following site preparation treatments. Direct seeding results in high stock density and natural development of root systems and large areas can be treated with limited time and personnel (Baumhauer et al. 2005; Hedin 1985; Corbett 1992; Reynolds 1997; Robinson 1974; Rudolph 1974). In direct seeding, seed is placed directly on scarified seedbeds and the spacing between rows and within rows can be controlled by modifying the application rate of the seed (Corbett 1992; Davidson 1992; Bulley and Bowling 1995). Seeders used for ground-based treatments are attached to a carrier and operate either manually or mechanically. All seeders have a hopper, a metering mechanism, seed delivery system and power source. Early trials with direct seeding using ground-based equipment resulted in inadequate seed densities and prime movers being under-powered for the seeding implement (Dominy 1991; Reynolds 1997). Dominy (1991) suggested modifications to the seed delivery tubes and concluded that prime movers with 32 amps excess electrical generating capacity are required to address the earlier problems (Dominy 1991).

Three factors are identified in influencing success of direct seeding: adequate seedbed preparation, seed/seedling ratios, and seed and germinant predators (Hedin 1985). Direct seeding without site preparation is unlikely to result in success (Mitchell et al. 1990; Robinson 1974). The British Columbia Ministry of Forests Silviculture Manual from 1982 recommended at least 25% (40% is preferred) mineral soil exposure to ensure successful regeneration from seeding (Hedin 1985; Mitchell et al. 1990). Moisture rates during the growing season also need to be considered, as a rich, moist site may have excessive brush competition that makes it unsuitable for direct seeding.

Seed to seedling ratios depend on the viability of the seeds, weather, seedbed, predation, competing vegetation and other factors that influence establishment and survival (Hedin 1985). Mann (1970) recommends using seed with no less than 80% viability to ensure adequate regeneration in seeding operations. The British Columbia Ministry of Forests has an average germination rate of 95% for seedlots available through SPAR. Seeding rates used for jack pine in Ontario are 50 000–74 000 seeds/ha for aerial seeding and 12 000–25 000 seeds/ha for spot or row seeding (Robinson 1974). The British Columbia Ministry of Forests recommended 0.3–0.5 kg/ha of lodgepole pine seed for broadcast seeding, 0.03–0.05 kg/ha for spot treatments and 0.06–0.11 kg/ha for furrow seeding at 2

m spacing. This works out to 100 000–168 000, 5000–8000, and 20 000–40 000 seeds/ha for broadcast, spot and furrow seeding, respectively (Hedin 1985).

Rodents such as deer mice (*Peromyscus maniculatus*) and chipmunks (*Tamias* spp.) have an annual cycle and can be a problem every year, while the voles (*Microtus* spp.) have a 3–4 year population cycle with increased seed predation during peak periods (Sullivan et al. 1990; Sullivan 1997). Seeding treatments should be timed to match the low periods in the cycle to minimize the impact on the success of the treatment (Sullivan 1997). Several control techniques have been tried: primarily poison baits and seed repellents, but most failed. The use of an alternative food source (sunflower seeds) showed promising results under experimental conditions and this method could be adapted for both aerial and mechanized ground-based seeding treatments (Sullivan and Sullivan 1982). Synthetic predator odour repellents are being developed to repel voles and attract their predators.

3.4 Costs of regeneration methods

Cost comparisons of alternative regeneration methods are affected by logging decisions (method and timing), seed supply (quantity and quality), seedlings (availability), capital budget (seed processing and storage facilities), manpower (seeding contractors and equipment, and experienced planters), administration (experience with seeding), laws and regulations (stocking levels and treatment acceptability), and environmental factors (site limitations, vegetative competition and seasonal weather) (Vyse 1974).

Natural regeneration has the lowest cost in the short term, but may require costly interventions later to increase stocking to an acceptable level and density. These treatments may include removal of the overstory, site preparation, and fill planting or seeding. Clumpy regeneration may require spacing to reduce local overstocking.

Hand seeding is more common than aerial seeding and Hellum (1974) found costs were 40% of planting costs. Mitchell et al. (1990) estimated that at 80% success rate, regeneration costs were $600/ha for aerial seeding and $900/ha for planting and at 60% success rate, costs were $1300/ha for aerial seeding and $1250/ha for planting.

Reynolds (1999) examined the costs associated with four regeneration systems for jack pine including aerial seeding, manual seeding with and without site preparation and seeding during site preparation, and compared them to planting costs. Seeding during site preparation ($567/ha) and aerial seeding ($755/ha) were the most cost effective treatments, followed by the two manual seeding systems ($850/ha without site preparation and $950/ha with site preparation) and then planting ($991/ha) (Reynolds 1999). These costs included seed acquisition, site preparation, stand establishment and juvenile spacing if required.

Sidders (1993) found seeding at the time of site preparation cost $178/ha compared to planting jack pine at $992/ha. Direct seeding was estimated at $350/ha while planting will cost $700/ha (Thomson 2005). Vyse (1974) compared broadcast seeding with planting and found that planting costs per hectare were lower because of the high seed costs, low planting costs and a low probability of the seeding achieving target stocking

levels. If broadcast seeding results in a 60% probability of achieving a stocking level of 1400 stems per hectare (sph), then costs are more favourable than planting.

3.5 Site preparation treatments

3.5.1 Removal of standing dead trees

In mountain pine beetle–killed stands, some intervention may be necessary before regeneration can succeed. These stands require treatments to overcome excess coarse woody debris on the ground, lack of suitable seedbeds and standing dead trees. Mountain pine beetle–killed lodgepole pines that are not harvested will eventually rot and fall down, impede wildlife and create a fire hazard and can affect visual quality and restrict travel through the stand (VanDenburg 1988; Jorgensen 2002). Historically, mountain pine beetle epidemics were followed several decades later by stand-replacing fires (Wyman and Alexander 1985; Agee 1994; Samman and Logan 2000; Amman 1988; Gibson 1988). Fire hazard is highest in the first five years after beetle attack when the needles and fine branches are retained on the dead trees (Environment Canada 1982; Gara et al. 1985; Turner et al. 1999; Forest Research Council 1983). At this time, there is a high probability of a crown fire as only a minimal period of drying weather is needed and moderate winds would sustain a crown fire (Environment Canada 1982). Then as the bark begins to slough off and trees begin to fall, the high fuel loading leads to stand-replacing fires (Environment Canada 1982; Gara et al. 1985; Logan and Powell 2001).

Mitchell and Preisler (1998) found that mountain pine beetle–killed trees fall to the ground after 3 years in thinned stands and 5 years in unthinned stands. In thinned stands, 50% of the beetle-killed trees were down in 8 years and 90% were down in 12 years. In unthinned stands, 50% of the beetle-killed trees were down in 9 years and 90% down by 14 years. The fall down rate seems to be related to the speed of bole decay at the ground level which is affected by light, temperature, wind and moisture. The fallen snags can result in large amounts of fuel and become an obstruction to regeneration. In contrast to Mitchell and Preisler (1998), Rakochy (2005) found that no beetle-killed pine had fallen in any of the plots left unharvested 0–9 years since attack.

When fire is removed from the ecosystem and beetle infestations kill large dominant lodgepole pine, shade tolerant species increase in growth and eventually pine will be eliminated from the stand (Amman 1976; Jorgensen 2002). When large accumulations of beetle-killed pine provide fuel for an intense fire, Douglas-fir and subalpine fir are killed and pine regenerates again (Amman 1976; Amman and Schmitz 1988). Keane (2000) found whitebark pine (*Pinus albicaulis*) killed by mountain pine beetle and blister rust (*Cronartium ribicola*) was replaced with shade-tolerant subalpine fir and spruce when there were no fires. Fires were needed to create conditions for regeneration of pine (Keane 2000), and whitebark pine in surrounding stands need to be protected from mountain pine beetle using verbenone pouches to ensure an adequate seed source for regeneration (Kegley et al. 2003).

If not salvaged, pure or nearly pure pine stands with serotinous cones will regenerate slowly and density will be low. Fill planting (Environment Canada 1982) or other alternative regeneration methods and site preparation treatments (Rakochy 2005) may be necessary to increase stocking to an acceptable level.

FERIC has examined several site preparation treatments for rehabilitating burned sties that have residual trees and these will be discussed in more detail in the next section.

3.5.2 Seedbed preparation

When there are abundant cones with viable seeds on the site but a lack of suitable seedbed, drag scarification is an option (Bancroft 1996). Dragging only moves cones a short distance and should be done in the first season after harvesting. If dragging is done in the second season, germinants will be killed or the released seed will be buried (Bancroft 1996; Clark 1984; Ferdinand 1983; Thompson 1978). Ferdinand (1983) found that north of the 53° latitude in Alberta, a delay of one year caused regeneration failure, but in the southern part of the province scarification could wait one year. McLarnon (1999) found that survival was highest in a unit that had been processed at the roadside without site preparation and lowest in a unit that was processed at the stump and chain dragged. The site preparation treatment occurred late in the season, and the cones had probably already released their seed and were subsequently destroyed during site preparation (McLarnon 1999).

If mineral soil exposure is too high, excessive stocking may result. Overstocking can be reduced by delaying scarification by one year after logging to intentionally kill some of the germinants or by windrowing the slash by piling and burning the piles (Forest Research Council 1983; Ferdinand 1983). Thompson (1978) found that in fresh logging slash with adequate cones (minimum of 9 cones/m^2), 60% mineral soil exposure was required to achieve 50% stocking or 1200 sph after four years. If scarification was delayed one year, 80%–85% mineral soil exposure was needed to achieve 1200 sph.

Drag scarification prime movers can be tracked or wheeled and a v-bar is used to attach drums, chains or barrels to help space out the implements (Bancroft 1996). The links in the chain can be light or heavy and can have grouser bars added. Shark-fin barrels are used to orientate the slash and expose the mineral soil in thicker forest floor conditions (Bancroft 1996). If a brush rake is used, a wide-toothed rake should be chosen so light slash cover remains to help reduce temperature extremes (Lotan and Perry 1983).

Harvesting during summer results in more mineral soil exposure than winter logging; however, not all this is suitable seedbed and scarification may be needed (Clark 1974; Han-Sup and Renzie 2001). Seed can be lost during logging if tops are skidded to the landing. Clark (1974) found up to 50% of the cones can be crushed, buried or removed during harvesting with a feller-buncher and grapple skidder system when the bunches are skidded to the landing. Therefore, surveys to determine the number of cones on the site should be done after harvesting (Vyse and Navratil 1985). The optimum situation is where some serotinous cone-bearing slash is left scattered over the harvested areas and the areas are scarified to provide a high-quality seedbed (Clark 1974). Drag scarification

crushes the cones and leaves them within 15 cm of the ground where the temperature of 45°–50°C occurs to break the resin bonds (Forest Research Council 1983; Lotan and Perry 1983).

In mountain pine beetle–killed stands, residual trees will interfere with site preparation treatments. Post-disturbance conditions are similar to wildfire. In several FERIC studies (Cormier 1998; Cormier 2000a; Cormier 2000b; Cormier 2001; Cormier and Provencher 1997), site preparation techniques for rehabilitating burned sites were examined. Regeneration problems following wildfires result from climatic conditions, lack of suitable seedbeds, the original stand condition, and lack of seed. Although some of the studies were in stands without serotinous cones, some of the observations made during these studies could be applied to mountain pine beetle–killed stands. Planning of site preparation operations after a fire (or beetle infestation), is complicated by the residual trees, the large size of the area affected and variability in the conditions, and the accessibility of the stands (Cormier 2000a; Cormier 2000b). The suitable equipment will depend on the condition of the site and on the stand before the disturbance, as well as the level of salvage, if any, after the disturbance. In stands that have been salvaged, a light scarification is generally sufficient, but heavy scarification may be required in stands with little or no salvage (Cormier 2000a).

Various trials have been carried out in Quebec and Ontario including using a Letourneau crusher to knock down the residual trees and a disc trencher to create planting spots (Cormier 2000a; Cormier 200b; Cormier 1998). On sites with dense debris, a V-rake was added to windrow the slash before disc trenching. Crawler tractors with rakes were also used to windrow the slash.

In Cormier and Warren (1998), five site preparation methods after a wildfire were compared including windrowing, crushing, harvesting with a feller buncher, and crushing followed by windrowing. The treatments were completed in the winter to minimize excessive soil disturbance. The results were compared to a windrowing treatment the following summer in the same wildfire. The winter treatments had less soil disturbance than the summer treatments (24% compared to 50%), but did not produce as many plantable spots. The winter treatments had a plantability level ranging from 28% to 44%, while the summer treatments had a plantability of 92% (Cormier and Warren 1998). The winter treatments required follow up treatments before planting could occur.

Cormier (2000a) presents nine site preparation strategies for burned sites. The costs of direct planting or passive scarification was $35–$135/ha, while crushing standing trees, windrowing with a V-rake and scarifying was $700/ha. Crushing and scarifying was estimated at $520/ha and a rehabilitation cut with a feller-buncher followed by scarifying was estimated at $600/ha. All of the methods assume that planting will follow, but seeding could occur when seedbeds are available and a natural seed source is unavailable. It is important to match the type of site preparation treatment with the site conditions as the costs can vary considerably.

Site preparation in unharvested stands, small openings and single tree removal will result in increased costs over conventional site preparation treatments following harvesting. Residual trees will increase the operational costs, reduce the treatment options, restrict travel within the stand, and increase safety concerns for workers and machine operators.

3.6 Natural regeneration after natural disturbances

Regeneration after wildfire will depend on the availability of seed which is determined by the proportion of serotinous trees in the stand and the intensity of the fire (Anderson et al. 2004). Regeneration following the Yellowstone Park fire in 1988 was rapid during the first four years (Turner et al. 1999; Romme et al. 2004). Charron and Greene (2002) also found recruitment peaked immediately after a wildfire and decreased to almost zero after the fourth year. Johnstone et al. (2004) found recruitment rates were highest in the first 5 years after a fire and no additional establishment occurred after 10 years. For successful natural regeneration after a wildfire a receptive seedbed must be available.

In a study examining the effects of crown fires on jack pine regeneration in the Northwest Territories, post-fire seed fall was found to be variable and influenced by fine fuel consumption and fire intensity, tree height, and height to the base of the live crown where the cones are located (de Groot et al. 2004). Germination rates were inversely proportional to length of fire duration. Seeds came from the upper canopy as the ones in the lower canopy were consumed in the fire. Regeneration was affected by site quality, post-fire weather conditions, and the seed source (de Groot et al. 2004).

A study to examine the generation capacity of seed from cones exposed to a simulated crown fire found that cones exposed for 10–20 seconds had germination capacity of 37%–64% (Despain et al. 1996).

Kashian et al. (2004) and Turner et al. (1997) looked at regeneration after wildfires and evaluated the relationship between the density of regeneration and fire intensity and size. They found that the burned patches varied in size and distribution and stand-replacing fires resulted in heterogeneous not homogeneous forest landscapes. Turner et al. (1997) found larger burned patches had more tree seedlings, greater densities of lodgepole pine and lower species richness than smaller patches. DeLong and Tanner (1996) found natural regeneration after wildfires resulted in uneven-aged stand structures and complex regeneration patterns due to variability in fire intensity and cone serotiny. Re-colonization of pine was quick due to the serotinous cones, available seedbed and minimal vegetative competition. Kashian et al. (2004) also compared the season of the burn to fire pattern and found that summer burns were more likely to remain on the surface and not become crown fires. MacLean (2004) found a summer fire requires more surface fuel to support a fire sufficiently hot to consume the moist green understory vegetation in the stand at that time of the year. In a stand killed by the Eastern spruce budworm, the fire hazard was most severe before green-up in the spring.

The volcanic eruption of Mount St. Helens on May 18, 1980, destroyed 61 000 ha of forested land (Means et al. 1982). Revegetation has been limited by surviving plants

resprouting and by seed dispersal from surrounding areas. The surface is nutrient poor tephra, ash and pumice, but below is fertile mineral soil. Lodgepole pine germination was delayed by the failure of the seed to penetrate the crust of ash, drought and extreme temperatures, but overall germination rates are showing promising results (Radwan and Campbell 1981; Frenzen and Franklin 1985). Frequent fertilizer applications are necessary to compensate for the poor nutrient status in the surface material (Radwan and Campbell 1981) and cultivation will break up the surface crust (Frenzen and Franklin 1985).

Large scale infestations can severely affect the hydrological cycles of the stand. These include canopy interception, transpiration, soil moisture storage, ground water levels and recharge, snowfall, snow melt, runoff and peak flows, food estimation, stream and stream bank stability erosion and sedimentation.[4] Excess moisture may become an issue, as the water table level rises after the stand is killed by mountain pine beetle, changing summer logging ground into winter logging ground and increasing operational costs for the contractors and Licensees. Site preparation treatment options may be restricted. On sites where excessive drying is a problem, leaving coarse woody debris can help in retaining snow and reduce erosion.

3.7 Regeneration and restoration opportunities

During the current mountain pine beetle epidemic in British Columbia seven million hectares are estimated as being infested.[1] Thirty percent to forty-five percent of the beetle-killed pine is not expected to be harvested due to limitations of demand, road access, management constraints, high harvesting costs, low product value, distance to market and other resource values (Fiedler 1988; British Columbia Ministry of Forests 2004; Eng 2004; Environment Canada 1982). The impact to the forest industry will be unprecedented if these stands do not regenerate naturally.

The social and economic impacts to the forest industry and the forest-dependent communities can be reduced if the mountain pine beetle-infested areas are regenerated quickly (Pedersen 2004), but regeneration should be prompt and well planned (VanDenburg 1988). Clearcutting is one of the best management options for converting mature lodgepole pine stands to younger stands, but this may not be possible in all cases. Regenerating stands that were killed by the mountain pine beetle provides the opportunity to create a stand that will be less susceptible to mountain pine beetle in the future.

Harvesting beetle-killed pine may recover volume and value that would otherwise be lost, reduce the fire hazard, reduce the visual impact of dead trees, reduce the impact of falling trees, and encourage pine regeneration by reducing the amount of shade and creating soil disturbance (Jorgensen 2002).

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[4] "MPB Salvage – Hydrology recommendations". Available online from: http://www.for.gov.bc.ca/hfp/mountain_pine_beetle/stewardship/Hydrological%20Recommendations%20Dec%203%202004.pdf. [Web publisher: BC Ministry of Forests. Posted Dec 8, 2004. Viewed March 24, 2005].

Salvage harvesting should only be done on the timber harvesting land base, leaving the non-contributing land base to follow a natural disturbance pattern of stand succession (Eng 2004; British Columbia Ministry of Forests 2004). Salvage in the wildland-urban interface should be conducted only to reduce fire risk (Eng 2004).

Cole and Amman (1980) suggest breaking up continuous pine stands by varying age and size classes to reduce the susceptibility to mountain pine beetle. This is repeated by Samman and Logan (2000). They point out that the results from mountain pine beetle infestations in wilderness areas, where the approach is usually no salvage, indicate that aesthetics may not be pleasing, access for recreation and wildlife will be hindered and the fuel build up from the dead trees may lead to fire management concerns. Heinselman (1971) had six policies for mountain pine beetle–killed trees in wilderness areas: attempt fire exclusion; allow safe lightning-caused fires to burn, but extinguish the rest; allow safe lightning-caused fires to burn and prescribe fires for other areas; suppress all wildfires and use prescribed fires to mimic nature; allow all wildfires to burn; and use full-scale vegetation and environmental manipulation by mechanical, chemical, seeding and planting to produce the desired vegetation. Consequently, mosaics of different age and size classes can be created by using fire, natural or prescribed, to reduce the impact of future mountain pine beetle infestations (Heinselman 1971).

Prescribed burning will release seed from serotinous cones, and remove overhead cover or slash, but some soil disturbance is required, as pine prefers mineral soil rather than burnt organic seedbeds (Feller 1982; Greene et al. 2004). If burning is delayed until after the seed fall, seed and germinants may be destroyed and soil damaged if the fire is intense (Feller 1982).

On a strictly economic basis, site rehabilitation is a poor investment (R&S Rogers Consulting Inc. 2001). Managers need to separate the site rehabilitation treatments from the silvicultural obligations to restore the site to full commercial productivity. Most mountain pine beetle–killed stands have some residual trees, either non-pine species or smaller younger pine that was not attacked (R&S Rogers Consulting Inc. 2001). Rehabilitation is not needed if the residual trees release and stocking is sufficient.

Huang et al. (2004) compared the growth rates of lodgepole pine stands in Alberta following harvesting and drag scarification with fire-origin stands with no treatment. The results showed that stands that had been harvested and scarified had 27%–35% higher growth rates. The stands are now 31 years old, although the increases in site index estimates were stable after five years suggesting that the increases in site index in the post-harvest stands were not a short-term result (Huang et al. 2004). These results support the idea of harvesting and scarifying the beetle-killed stands to get them back into production rather that waiting for a stand-replacing fire to initiate the regeneration phase.

4 Conclusions/recommendations

During the current infestation, not all the mountain pine beetle–killed lodgepole pine trees will be harvested. Some of these stands will need assistance to regenerate them and

bring them back into production. Because of the scale of the mountain pine beetle infestation, a range of treatments will be needed from the simple "do nothing approach" and let nature take its course, through to an "intensive intervention" including removing the residual trees, carrying out site preparation and seeding or planting. The most suitable treatment for the site will depend on the stand condition before the attack, the level of attack, the location of the stand and the site quality. Treatment costs will increase with increasing constraints and operational difficulties.

Natural regeneration is preferred to minimize costs in the short term and to allow natural root systems to develop. When natural regeneration fails due to a lack of viable seed, planting or seeding may be required. Natural regeneration and seeding requires a suitable seedbed created by harvesting, drag scarification, disc trenching, piling and burning or broadcast burning. Any treatment should emphasize the production of suitable seedbeds. Although direct seeding is not currently recognized by the B.C. Ministry of Forests as a standard reforestation method (but can be tried on an experimental condition), it has the potential to create seedbed and provide seed to a large area at a reasonable cost.

Residual trees in beetle-killed stands need to be addressed (e.g., cut down, knock down, crushed or burned) to reduce the obstruction for site preparation equipment and to reduce the hazard to the workers or machine operators. Any remaining residual trees need to be monitored periodically for changes in condition.

Existing equipment should be used, if suitable, to minimize costs and maximize cost efficiencies for contractors. Treatments need to be coordinated to share specialized equipment (e.g., seeders on disc trenchers) with other Licensees or contractors.

One regeneration method will not provide the same results on all sites. The condition of the residual stand is influenced by the percentage of stand killed by beetle, the original stand composition, and natural disturbance pattern. Forest managers are encouraged to use a variety of methods and monitor the results over time.

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